Resources for the Design of Data Fusion Systems*

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Abstract - *This paper outlines the data fusion process from a military perspective and discusses resources available for the design of interoperable systems. It is stated that data fusion should be viewed as a systems engineering process. The resources include government sponsored fusion models, process architectures, and message standards; various research programs; systems integration facilities; data sets and development tools for analysis and simulation; public forums of conferences, symposiums, and workshops; and government publications. Some potential areas for future data fusion research are discussed. Numerous online web sites are referenced to provide starting points for obtaining additional information.*

Key Words sensors, military, data fusion, system design, database, architecture.

1. Introduction

This paper is gives an introduction to the field of data fusion and provides system developers with the knowledge of available resources. The Space and Naval Warfare (SPAWAR) Systems Center in San Diego (SSC-SD) has played an active role in many of the programs and working groups discussed. However, this paper is not completely comprehensive in nature and should only be viewed as a starting point for further investigation of data fusion and resources for the design of systems. The integration of higher level data may be referred to as information fusion and the content may be differentiated in specific knowledge domains. In this paper data fusion and information fusion will be used interchangeably.

2. System Design

The discipline of systems engineering provides procedures and tools to enable the design of data fusion and other complex systems. This paper will not address methodologies of conducting systems engineering. Nevertheless, the development of data fusion systems should be viewed as a system engineering process. The U.S. government has published a number of useful references to facilitate the design of systems. The Electronic Industry Association (EIA) developed systems engineering standard IS-632 that provides guidance for the conduct of systems engineering efforts. There is also a Systems Engineering Capability Model standard IS-731 to assess capability. The International Council on Systems Engineering has resources online at http://www.incose.org/

2.1 Data Fusion Process

The process of bringing large amounts of dissimilar information together into a more comprehensive and easily manageable form is known as data fusion. This process, as shown in Figure 1, involves a large number of disciplines including signal and imagery processing, control theory, database design, networks, data standards, and Human Computer Interface (HCI). Military research applicable to data fusion is done in the areas of Intelligence Surveillance and Reconnaissance (ISR) sensors, Command and Control (C2), Communications (C), and Computers that collectively comprise C4ISR. Data fusion comprises a very broad field of research. The programs discussed are dynamic and changes are likely to occur from the time of this publication.

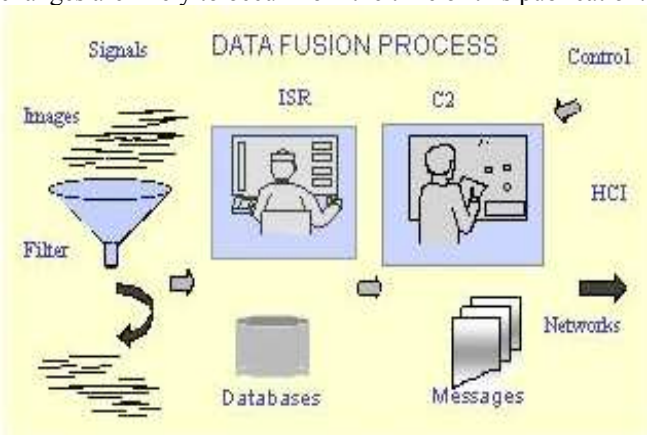

Figure 1 Data Fusion Process. Data fusion involves a number of disciplines including signal and image processing, database design, and control theory.

2.2 Data Fusion Models

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In 1991, the Joint Director of Laboratories (JDL) Data Fusion Sub-panel (DFS) published a data fusion model and lexicon which have become well known references for the data fusion process [1]. The JDL model, as shown in Figure 2, consists of an input of sensors and external sources and an output display to an operator and subsequently to other processing nodes. The four processing steps are as follows:

1) Object refinement consists of data association, target tracking, classification, and combat ID (i.e. declaration of friendly, hostile, or neutral).

2) Situation refinement or assessment includes track-to-track correlation and the inclusion of all relevant information into a situation display.

3) Threat refinement consists of the assessment of activity and intent of entities. The assessment of intent is dependent on situational context.

4) Process refinement or resource allocation enables process control and performance enhancement. Resource allocation is needed for efficient movement of data through the battle-space and involves making performance tradeoffs.

This model has been recently updated to include level 0 which consists of preprocessing of sensor data including target feature and attribute extraction [2]. The military context of the data fusion model and lexicon has been broadened to include non-military applications. A new definition and lexicon has been proposed by the European Association of Remote Sensing Laboratories (EARSeL). In a broader context "Data fusion is a formal framework in which are expressed means and tools for the alliance of data originating from different sources [3]."

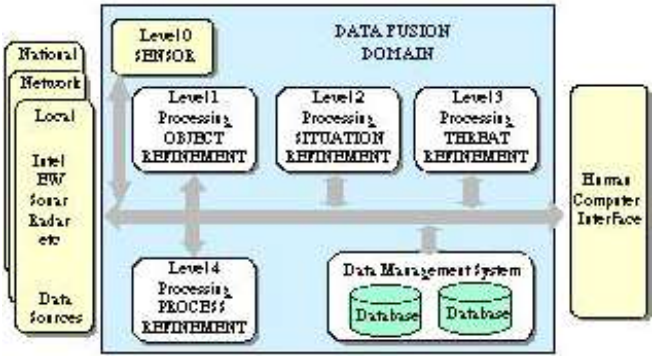

Figure 2 Data Fusion Model. The data fusion model developed by JDL/DFS consists of sensors/ sources for input, four levels of processing, and operator display for output.

2.3 Data Fusion Architectures

Several architectures are possible for combining information. Data can be associated at the measurement, feature or decision level in each of the data fusion levels. Additionally, the fusion process can address hybrids of data abstraction within one fusion node. Target identification involves doing feature extraction, comparing features to an a priori database and making a declaration [4]. Imagery feature extraction is more difficult than signal feature extraction in most problem domains. However, some progress is being made with 2-D radar imagery sensors such as Inverse Synthetic Aperture Radar (ISAR) [5].

In 1998, the Chief of Naval Operations designated NAVSEA 05 responsible for Combat ID (CNO letter 021648Z May 98). The Combat ID Systems Engineering Team (CID SET) was established with 5 working groups: Multi-Sensor Integration (MSI), Intelligence Surveillance and Reconnaissance (ISR), Database Requirements (DR), Indications Friend Foe (IFF), and ID. Shown in Figure 3 is a notional architecture for data fusion that this group recommended and was later modified by SSC-SD. The CID SET coordinates its activity with the All Service Combat ID Evaluation Team (ASCIET). The ASCIET uses exercises to evaluate interoperability and recommend changes to Combat ID for air and land warfare. These exercises are sponsored by Joint Forces Command.

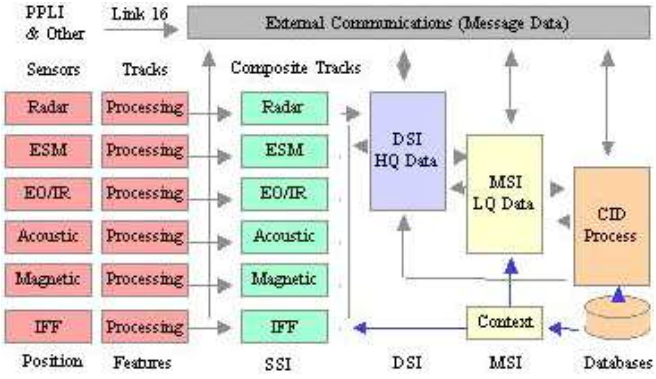

Figure 3 Data Fusion Architecture. Notional architecture, developed by CID SET and modified by SSC, defines the framework of a system or how the pieces fit together.

In 2000, the Navy was given the lead role for systems engineering of Single Integrated Air Picture (SIAP). A Joint office was established (JROC memo 97-00 dated 25 May 2000) which will provide direction for future data fusion architecture refinements and fusion system developments. In addition, requirements for a Single Integrated Picture (SIP) are being reviewed by OPNAV N81. The National Defense Industrial Association (NDIA) is defining requirements for SIP in all warfare areas but will focus initially on surface and subsurface pictures.

2.4 Network Centric Warfare

Network Centric Warfare (NCW) requires common communication networks, message data elements, and processing methods. As shown in Figure 4, many network nodes exist and many are mobile.

Communications exist as broadcasts and networks. Data comes together in non real-time over Joint Planning Networks (JPN), in near real time over Joint Data Networks (JDN) and in real time over Joint Composite Tracking Networks (JCTN). The JPNs consist primarily of satellite subscriber broadcasts such as OTCIXS and TDDS. The JDNs are comprised of tactical networks such as Link-11 and Link-16. The JCTNs consist of fire support networks such as the Data Dissemination System (DDS) of Cooperative Engagement Capability (CEC).

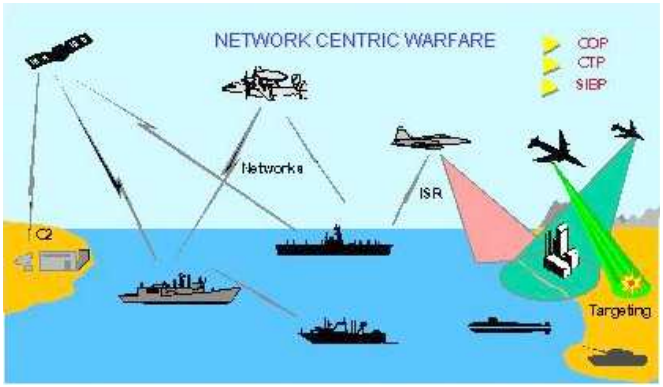

Figure 4 Network Centric Warfare. Joint interoperability requires a single integrated picture based on a commonality of networks, data sets, and processing methods.

Standard message sets are used to send structured data between platforms and command centers. Collaborative tracking relies on track reports which have position and kinematics data; classification and supporting parametric data; and target ID (i.e. hostile, friendly or neutral). Message sets can be character oriented such as man readable Over-The horizon Gold (OTG) messages or bit oriented such as Link-16 J series messages. The DOD directive 8320.1 establishes a Defense Data Dictionary System (DDDS) to improve interoperability. The NATO Standard Agreement (STANAG) 4420 provides taxonomy of targets. This and other documents can be either downloaded or ordered online http://stinet.dtic.mil/.

Uniform processing is required to create a Common Operational Picture (COP), Consistent Tactical Picture (CTP), and Single Integrated Battle Picture (SIBP). These pictures support a military command hierarchy and as such are differentiated in scale of area of interest, degree of fidelity and timeliness of information. Typically, platforms initiate and maintain "local" tracks and track-to-track correlation of "global" tracks is done at Command and Control (C2) sites. Display standards exist for common representation such as DOD military standard 2525 version B (published 1999). Processing standards exist in the form of Defense Information Infrastructure Common Operating Environment (DII COE) sponsored by Defense Information System Agency (DISA) http://diicoe.disa.mil/coe/

3. Data Fusion Systems

There are currently over a hundred Tactical Data Processors (TDPs) that can be considered data fusion systems [6]. Most of these systems support specific platforms and applications. The focus of most data fusion research is on how to automate information processing. This is because one of the largest problems facing operators at command centers today is how to deal with the large quantities of data arriving at their doorstep. An open architecture for data exchange and correlation is necessary to enable collaborative solutions that are supportable by multiple programs.

3.1 Fielded Systems

Most sensor platforms contain data fusion engines as a part of the electronic suite. A few systems are not linked to specific platforms and are used to fuse information at Command and Control (C2) Sites. These systems include the following military systems:

1. GCCS - The Global Command and Control System - Maritime (GCCS-M) provides an all source picture but focuses on ship and submarines. It has been built by the Navy on a distributed platform architecture. The program is run by SPAWAR and sponsored by DISA. For program details see http://www.disa.mil/disahomejs.html.

2. ASAS - The All Source Analysis System (ASAS) provides an all source picture but focuses on land targets and requires a broadcast of data to a central fusion site for distribution. The program is sponsored by Army Training and Document Command (TRADOC). For program details see http://www.tsmasas.army.mil/

3. TBMCS - The Theater Battle Management Core System (TBMCS) includes three primary sources of intelligence: signals (SIGINT), imagery, and Maritime Intelligence database (MIDB). The AA segment (algorithm from BTG) associates the SIGINT/tracks and an MIDB site. The I3 segment links an image with the MIDB using the National Imagery Transmission Format (NITF) header. For program details see http://tbmcs.af.mil/

4. CTT - The Commanders Tactical Terminal (CTT) will receive and display tactical intelligence data at secret and higher levels of classification. The data is received from TRIXS, TIBS, TRAP, and TADIXS B intelligence broadcasts. The Multi-mission Advanced Tactical Terminal (MATT) is a near term substitute. For details see http://www.fas.org/irp/program/disseminate/ctt.htm

Most systems have attribute correlators (e.g. electronic intelligence or ELINT) for automated classification but rely on operators for target ID assignment and Track-To-Track correlation. A need exists for design of more automated processes to perform these functions.

3.2 Research Programs

Many Research and Development (R&D) programs do work in data fusion but only a few focus primarily on this technology. Some of the programs being supported by SSC-SD that focus on data fusion are as follows:

1. TSF - The Target Tracking and Sensor Fusion program is conducting basic research in target tracking. The program emphasis is on developing tracking algorithms, network architectures and performance benchmarks. The work is sponsored by ONR 31. For program details see http://www.onr.navy.mil/sci_tech/information/#surveillance

2. TCT - Theater Collaborative Tracking (TCT) program is exploring future capabilities to track air targets using Link-16, CEC Data Distribution System (DDS), and/or other network combinations. The focus of the program is on means to track and classify rapidly maneuvering targets such as aircraft and missiles. This work is being led by SSC-SD and sponsored by ONR 31 [7].

3. DADS - Deployable Autonomous Distributed System (DADS) program is working on underwater sensor networks that perform multi-sensor data fusion at the sensor level and network level. Sensors communicate through acoustic modems. This work is led by SSC and sponsored by ONR 32 http://www.onr.navy.mil/sci_tech/ocean/onrpgahd.htm.

4. DDB - The Dynamic Database (DDB) program is investigating methods to link data from multiple databases and provide relevant content to operators. This program is addressing a broad range of fusion technologies. This work is sponsored by DARPA and details can be found at http://www.darpa.mil/tto/programs/ddb.html.

A number of other research programs exist. Most fusion R&D work is being done is on JDL levels 1 and 2. Much less work is being done on levels 3 or level 4. The reason may be that work on the JDL levels relies on inference processes and these can grow in complexity with levels. In addition, the work at higher levels requires understanding of cognitive processes.

4. Design Resources

The design of systems involves performance assessment. Performance Evaluation (PE) consists of lower level Measures of Performance (MOPs) and higher level Measures of Evaluation (MOEs). An example of a MOP would be detection probability of a specific tracker. An example of a MOE would be timeliness of information to support a decision. Use of common metrics can facilitate algorithm comparison during system design. Furthermore, use of common algorithms can improve software reuse and affordability of system development. The PE process typically incorporates a combination of detailed analysis, Monte Carlo simulation, laboratory based testing, and operational evaluation.

4.1 Test Facilities

Operational systems rely on system integration facilities to do research, development, configuration management and Test and Evaluation (T&E). Facilities at SSC-SD that support data fusion work are listed below.

1. ACE - Advanced Concept Engineering (ACE) laboratory does work on integration of tactical intelligence products. The lab supports several SPAWAR programs including Cryptologic Unified Build (CUB), Relocateable Over-The-Horizon Radar (ROTHR), Combat Direction Finding (CDF), and Naval Simulation System (NSS).

2. CCTC - Command Control Technology Center (CCTC) supports system integration using simulation. The lab supports Joint Semi-Automated Forces (JSAF) (formerly STOW), Extending Littoral Battlespace (ELB), and Joint Medical Semi-Automated Forces (JMEDSAF) ACTDs. For details see http://www-code44.spawar.navy.mil/

3. ADVISR - The Advanced Virtual ISR (ADVISR) laboratory supports virtual testing using High Performance Computers (HPCs). The lab supports Deployable Autonomous Distributed System (DADS) testing. Information on this and other simulations can be obtained at the Navy Modeling and Simulation Management Office at http://navmsmo.hq.navy.mil/index.cfm?RID=MNS_N_1001259

4. SIF - The System Integration Facility (SIF) uses commercial off the shelf tools to perform testing of tactical networks such as Link-16. The facility also supports the Distributed Engineering Plant (DEP) distributed simulation

for evaluation of ship connectivity prior to deployment. For details see http://www-c4516.nosc.mil/SIF1.html

4.2 Development Tools

There are a number of development tools available to assist in research. Data sets and algorithms are made available at little or no cost through universities or government agencies. Software for signal processing and other specific applications can be obtained through commercial vendors. Some available resources are listed below.

1. Toolkits - Data fusion toolkits have been developed by Advanced Research Laboratory (ARL) at Pennsylvania State College. These toolkits are in C++ and provide visual interface for sensor processing analysis [8]. Sensor modules exist for data sources, pre-processing, feature extraction, and identification. The analysis modules exist for association, estimation and ID.

2. Simulation - Tracking benchmark software has been sponsored by ONR 31 and BMDO [9]. The Naval Surface Warfare Center (NSWC) Benchmarks I through IV were developed to assess multiple sensors on a single platform. The Joint Composite Tracking Network (JCTN) and Tactical Ballistic Missile Defense (TBMD) Benchmarks were developed to assess network based tracking of air and missile targets respectively. For details see http://seal-www.gtri.gatech.edu/jctn/

3. Data Sets - The Sensor Data Management System (SDMS) provides imagery files (i.e. EO, IR, SAR) to support research in sensor integration. This work is done by Air Force Research Lab (AFRL) and is sponsored by DARPA. The data is available on CD-ROM and web at http://www.mbvlab.wpafb.af.mil/public/sdms/frontdoor.htm

4. Analysis - The formation of a Fusion Information Analysis Center (FUSIAC) is planned for bringing together resources for development of data fusion systems. Library documents and data sets will be available online in the summer of 2001. There are 13 IAC groups that are charted by OSD. Some information about these groups is online at http://www.dtic.mil/dtic/rtoc/iac.html.

5. Data Fusion Publications

Some excellent books have been published on data fusion and should be read for a subject overview. Three books have recently been published that provide data fusion overviews and discuss technologies used to support the design of systems [10], [11], and [12]. Material exists in the form of publications and government documentation. Conference agendas and most paper abstracts are available over the Internet. Journal papers are available through subscription over the Internet. The electronic media has the advantage of topic searches.

5.1 Conference Proceedings

Many publications have content relevant to data fusion but only a few focus specifically on this area. Publications that focus on data fusion are listed below:

1. Conference - The Fusion 2000 series is sponsored by International Society of Information Fusion (ISIF). This international unclassified conference discusses technology, algorithms and applications dealing with commercial and military systems. Information about this conference is at http://www.inforfusion.org/

2. Symposium -The National Symposium on Sensors and Data Fusion (NSSDF) is sponsored by Military Sensing Symposia (MSS). This US symposium offers a forum for the presentation of classified military papers. Information about this symposium can be obtained on the Internet at http://csdnta.erim-int.com/iria/irismeet.nsf

3. Workshop -The Target Tracking and Sensor Fusion Workshop is hosted by Georgia Tech Research Institute (GTRI) and sponsored by ONR. This small workshop is held annually and the proceedings are distributed on CD-ROM. Information is available online at http://seal-www.gtri.gatech.edu/jctn/

4. Journal - Information Fusion Journal was started in 2000 by Elsevier Science S. A. publications. Mr Belor V. Dasarathy is the editor. For information about this and other Elsevier online electronic publications go to http://www.elsevier.com/locate/inffus

5.2 Government Documents

Several documents exist which provide data fusion assessments, baselines for operational systems, network interoperability standards, and future military architectures. Some useful documents are as follows:

1. Assessment - The Joint Decision Support Center (DSC) for OASD (C3I) has studied Multi-INT Fusion Performance. This work has produced several useful products including an Information Needs Database (INDB) of Essential Elements of Information (EEI) used by the military. The group has created a methodology and associated metrics to evaluate ISR architectures and ability to meet the information needs

for specific missions. For details available online see http://www.dsc.osd.mil/

2. Baselines - The Advanced Data Fusion Science and Technology (S&T) initiative at SSC-SD has studied military use of information technologies. Papers have been published on sensor analysis and data mining [13]. Work is ongoing on network analysis and database structures. This work provides an understanding of the data flows in the battlespace used to support data fusion systems.

3. Architecture - Work at SSC-SD has been done on technical, system, and operational architectures. Government documents exist that describe "what an architecture is" and provide processes and tools for the design of interoperable systems. The C4ISR Architecture Framework V.2.1 and other documents can be found online at http://www.fas.org/irp/program/core/c4isr.htm

4. Designs - Engineering guidelines for correlation and fusion have been developed by the Project Correlation sponsored by the Tactical Exploitation and National Capabilities (TENCAP) office. A data fusion tree paradigm was developed which provides components, interfaces, and methodology for fusion software development. This paradigm supports an open, modular, and layered design for data integration [14]

6. Conclusions

Data fusion system design is a systems engineering process. This process involves defining customer needs (inputs), requirements analysis, functional allocation, product synthesis, and design reviews (outputs). To facilitate this process, organizations have attempted to provide a framework for the design of interoperable systems. This framework consists of a fusion model, a common lexicon, fusion architecture, and network message standards. Resources exist to help in the design process in the form of test facilities, development tools, and publications. These resources offer cost effective means to start the design of new systems and facilitate the upgrade of existing capabilities.

A large number of data fusion systems exist. The JDL model partitions the data fusion process into four levels representing common problem domains. Most research is being done on the lower JDL levels that represent more tractable problems. However, work is needed in on all levels to automate processing and reduce the workloads of operators. This is important in order to keep pace with the very rapid growth in information. Some potential areas of future work were pointed out in the paper. Network based solutions with open architectures are encouraged. A modular approach to design will enable software reuse.

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